C-CORE # 80-6

# AIRBORNE IMPULSE RADAR SOUNDING OF SEA ICE

# SONDAGE DES GLACES OCEANIQUES PAR RADAR AEROPORTE A IMPULSIONS

J.R. ROSSITER[1] K.A. BUTT[1] J.B. GAMBERG[1] T.F. RIDINGS[1]

## ABSTRACT

Airborne impulse radar, operated from helicopter and Twin-Otter, was used in March-April 1979 to estimate the physical properties of sea ice in the Beaufort Sea and Lake Melville, Labrador. Concurrent measurements included: augered thickness, salinity, temperature, crystal fabric, electrical properties of the ice, simultaneous aerial photography, and synthetic aperture radar imagery.

Impulse radar centre-frequency of 80, 100, 200 MHz appears to give the best trade-off of penetration vs resolution and antenna size. Data collected below 30 m elevation have reduced side-scatter from the ice surface. Speeds below 50 m $s^{-1}$ are required with the current hardware to achieve coherence from scan-to-scan.

Thickness estimates are excellent for fresh and brackish ice, and are good for undeformed first-year sea ice about 1-2 m thick. Areas of fresh water melt pools that have only experienced surface refreezing show thickness profiles that warrant further examination. Bottom returns from multiyear ice are sporadic, although floes up to 14 m have been sounded. Ridges are not usually penetrated, but can be easily detected. Data processing algorithms are under development to characterize the ice further using the strength of the returns. Airborne impulse radar appears useful for routine estimation of the "third-dimension" of ice properties, particularly in conjunction with aerial remote sensing surveys.

## RESUME

Un radar aéroporté à impulsions, opéré à partir d'un hélicoptère ou d'un Twin Otter, fut utilisé en mars et avril 1979 pour estimer les propriétés physiques des glaces marines dans la mer de Beaufort et dans le lac Melville, au Labrador. Les mesures simultanées suivantes furent prises: épaisseur déterminée au foret, salinité, température, structure cristalline, propriétés électriques de la glace, photographie aérienne simultanée, images obtenues par radar à ouverture synthétique.

Des fréquences centrées à 80, 100 et 200 MHz furent employées pour le radar à impulsions. Une fréquence centrée près de 100 MHz semble donner la meilleure pénétration, compte tenu de la résolution et des dimensions de l'antenne. Les données recueillies sous 30 m d'altitude montrent une réduction de la diffusion latérale en provenance de la glace. Avec l'équipment électronique actuel, des vitesses inférieures à 50 m/s sont nécessaires afin d'obtenir une cohérence dans les signaux d'un balayage à l'autre.

Les estimations des épaisseurs furent excellentes dans le cas des glaces d'eau douce et saumâtre, et sont bonnes pour les glaces non déformées, de première année et dont l'épaisseur est d'environ 1 à 2 m. Les zones ayant dégelé et, par après, n'ayant connu qu'un regel superficiel ont des profils d'épaisseur qui demandent un examen plus poussé. Les retours de la face inférieure des glaces âgées sont sporadiques, malgré que des banquises allant jusqu'à 14 m ont été sondées. Les crêtes ne sont habituellement pas pénétrables mais sont facilement détectables. Les algorithmes nécessaires au traitement des données sont présentement en cours d'élaboration et permettront de caractériser davantage les glaces en utilisant l'amplitude des signaux de retour. Le radar aéroporté à impulsions semble donc s'avérer utile pour l'estimation régulière de propriétés "tridimensionnelles" de la glace, particulièrement dans le cas des études conjointes avec la télédétection aérienne.

1) Centre for Cold Ocean Resources Engineering, Memorial University of Newfoundland, St. John's, Newfoundland. A1B 3X5

**KEYWORDS/MOTS-CLES:** Sea Ice, Short Pulse Radar, Arctic Ocean, Labrador, Ice Thickness; Lake, Synthetic Aperture, Ice Identification, Image Enhancement, Dielectric Properties.

Presented to the 6th Canadian Symposium on Remote Sensing, Halifax, Nova Scotia. May 21-23, 1980.

## INTRODUCTION

As more work is carried out in the Canadian Arctic during winter, there exists a greater need for the ability to make remote estimates of the physical properties of sea ice (Mercer, 1980). The critical properties are the thickness and strength of ice, whether it be for operations on the ice surface, or movement of ice-breaking vessels. Although progress has been made in recent years in the observation and classification of sea ice using remote sensors (Campbell et al., 1975), only limited success has been achieved in remote measurement of ice thickness and strength. This ability is particularly important because of the high variability and dynamic nature of sea ice and the increased industrial activity in Canada's North.

The most successful measurements to date use radar sounders operating in or near the VHF band (Rossiter, 1980), and a number of new instruments are actively being developed which have potential application to the remote determination of sea ice thickness (Rossiter and Bazeley, 1980).

Impulse radar systems, using broadband pulses in the 50 to 500 MHz frequency band, are being used routinely in the Arctic from surface vehicles. Active research work on sea ice is being pursued using these systems both at the Cold Regions Research and Engineering Laboratory in the U.S.A. (e.g. Kovacs and Morey, 1979) and at C-CORE (Rossiter et al., 1977; Butt and Gamberg, 1980).

This paper reports on C-CORE field measurements made in the Beaufort Sea during March 1979 (Rossiter and Butt, 1979) and over Lake Melville, Labrador in April 1979 (Butt et al., 1979). The sites were chosen to coincide in time and place with other investigations, including the SURSAT Project, which involved a number of sea ice studies (including other remote sensing overflights), and a Province of Newfoundland and Labrador study of Lake Melville ice conditions. Results from subsequent analysis of selected sites are presented.

In addition, enhancement of results that can be achieved through data processing are presented. In particular, cross correlation appears promising, and this technique is outlined here.

## DATA COLLECTION

### Beaufort Sea

The Beaufort Sea field program operated out of the Polar Continental Shelf Project base camp at Tuktoyaktuk, N.W.T. A description of the sites and a summary of the data as collected are presented in a separate report by Rossiter and Butt (1979). The positions of the sites are shown in Figure 1. The local sites, all of which were within a 75 km radius of Tuk, are designated as C-1 through C-6. Besides the radar work, concurrent ice measurements included: augered thickness, salinity, temperature (Snellen and Rossiter, 1980), crystal fabric (Langhorne, 1980; Langhorne et al., 1980), electrical properties of the ice (Davis, 1980), simultaneous aerial photography, and synthetic aperture radar imagery.

An area of multi-year ice, north of the shear zone, approximately 320 km north of Tuk and a few km south of Ice Island T-3, was studied by both C-CORE and SURSAT. Another area of interest was the ice rubble field at Issungnak, located approximately 75 km northwest of Tuk. Since the nature of this ice field restricted most conventional forms of ground truthing, only airborne data were collected.

### Lake Melville

The Lake Melville field program operated primarily out of Goose Bay, Labrador. A description of the sites and a summary of the data collected are presented in a separate report by Butt et al. (1979). The positions of the ground truth sites and radar overflights are shown in Figure 2.

Although not shown, SAR overflights were run down the Lake, covering the same area as the impulse radar. Surface truth data, provided by Remotec Applications Inc., consisted of ice thickness and salinity measurements. Remotec also provided a central weather station for temperature and local meteorological data.

## RESULTS

### Beaufort Sea

The Beaufort Sea field trip included the first use of impulse sounding radar from a fixed-wing aircraft platform (a de Havilland Twin Otter - see Figure 3). Although the installation was successful, it must be regarded as experimental. The aircraft was flown at 100 to 140 knots airspeed (50 to 70 m $s^{-1}$). The scan repetition rate of the impulse radar (51.2 scans/ second) is probably not fast enough for routine fixed-wing use, since only a single scan of data was collected per metre of forward movement. The ice characteristics can

change substantially in this distance, giving significant differences in returned signal from scan to scan, even over relatively uniform ice.

Data were collected at altitudes from 100 to 300 feet above sea level (30 to 100 m). There were noticeable differences between results from lower and higher level operation, caused primarily by the larger footprint of the radar at higher altitude. The antenna of the radar is a modified dipole, and the footprint size is the same order of magnitude as the flying height. It was found reasonably easy operationally to fly for several hours at 30 m elevation.

Measurements were made at a centre frequency of 200 MHz. Analysis of 440 line-km of data similar to Figure 4 over an area of multi-year ice in the Beaufort Sea indicated that penetration of multi-year ice was not consistent from floe to floe, or even within the same floe. However, the soundings obtained could be used to calculate a multi-year ice thickness distribution. The thickest floe measured had a calculated thickness of 13.5 m.

That study showed the utility of collecting simultaneous imaged data, in this case aerial photography. Photographs were taken both at low level from the aircraft containing the radar, and from 2440 m from a second Otter (Figure 5). Since the radar and photography were taken simultaneously, the flight path of the radar aircraft could be plotted, and the radar record correlated with ice features in the imagery. This allowed significant improvements to be made in the interpretation of the radar returns.

In particular it was possible to identify ice types from the nature of the radar echoes. Roughness on the scale of 1 to 10 metres horizontally is usually indicative of multi-year floes, which have a hummocked surface. First-year ice is either much smoother, or if deformed, much rougher (Figure 4). First-year ridges and rubble piles are made up of small blocks of ice which are excellent random scatterers at 100 MHz and give very weak surface echoes.

### Lake Melville

The ice in Lake Melville is formed from relatively fresh water, and the salinity is typically less than 2 ppt in the bottom 10 cm of ice layer. There is, however, a horizontal salinity gradient increasing from west to east along the lake. The two most significant runs with the impulse radar were the long runs from North West River to Gull Island at 100 MHz and 200 MHz centre-frequencies. Both of these runs showed the effect of the salinity gradient with reduced penetration at the east end. Overall, the best results were obtained at 100 MHz, where a complete profile of the entire lake thickness was obtained. Ground truthed thickness measurements increased systematically from about 85 cm in the west to about 140 cm in the east. This increase showed up clearly on the radar record. The correct value of the thickness was obtained using the measured travel times and a dielectric constant of 3.2. This value of dielectric constant is consistent with ice of relatively low brine volume.

Important features overflown in this study were so called "ridges" that might better be described as "hummocks". The radar was able to delineate the upper surface relief and width of the features. The surrounding ice showed no appreciable increase in thickness as the radar approached the well-defined edge. It is possible that impulse radar could be used to differentiate these hummocks from true ridges, which would be significantly thicker than surrounding ice and perhaps more difficult to break by ship.

Other features that stood out clearly in both the impulse radar and SAR records were refrozen melt ponds. Although these features were not examined by the surface party, they appeared from the air as circular areas of ice, several tens of metres in diameter, which had melted and later had refrozen to some depth. The impulse radar record showed these features with very pronounced V-shaped "bottom" echoes. Two interpretations are presented by Butt et al. (1979). One is based on the hyperbolic return profiles formed from point targets and a forward antenna velocity. The other relies on the presence of a water layer sandwiched between the refrozen top and original ice surfaces. However, due to slope variations in the hyperbolic tails and the need for a water layer in excess of 1 m thick in some places, neither of the explanations is wholly adequate. These features warrant further field investigation.

## DATA ENHANCEMENT

As suggested by Rossiter et al. (1977), the radar signal itself may be used to establish crudely the electrical properties of the ice. An attempt has been made to estimate the relative attenuation between the top and bottom ice surface reflections from the return echo strengths (Butt and Gamberg, 1980; Rossiter et al., 1980).

Measurement of the ice attenuation involves computation of the signal losses at each in-

terface of the air-snow-ice layers. For the case of no snow, attenuation can be calculated from:

$$E_b = E_t \times T_{ai} \times R_{iw} \times T_{ia} \times A \times \frac{1}{r^2} \quad (1)$$

where $E_b$ is the received intensity of the bottom echo,

$E_t$ is the intensity of the transmitted signal,

$T_{ai}$ is the transmission coefficient at the air-ice interface,

$R_{iw}$ is the reflection coefficient at the ice-water interface,

$T_{ia}$ is the transmission coefficient at the ice-air interface,

$A$ is the signal attenuation in the ice,

and $r$ is the total signal path.

We usually assume that the geometric spreading losses ($1/r^2$) are compensated for by the time-varying ($t^2$) gain of the receiver.

Studies indicate that the effective reflection coefficient of a snow layer is significant. If a snow layer is present then the apparent transmission coefficient should be calculated for substitution into (1) (Butt and Gamberg, 1980).

Having calculated the total attenuation and measured the pulse travel time through the medium, an empirical relationship as described by Rossiter et al (1980), can be used to form an estimate of the ice thickness without first having to assume a dielectric constant. The dielectric constant can then, in turn, be calculated. Received signal strength ($E_b$) is determined from the magnitude of the peak of the cross-correlation between the received signal and an estimate of the transmitted signal (replica pulse). The location of this peak is also used to accurately determine the arrival time of the received pulse.

Figure 6 shows a sample of unprocessed data collected in the Beaufort Sea using the GSSI impulse radar. Figure 7 is the result of the same data set from Figure 6 that has had the cross-correlation technique applied. It clearly demonstrates the feasibility of producing accurate estimates of top and bottom echo arrival times. Due to time-base accuracy in the radar system, most thickness results are calculated using a fixed dielectric constant near 4. From our data, this approximation gives thickness estimates accurate to $\pm$ 20% or better.

For ice displaying horizontal anisotropy (Kovacs and Morey, 1979; Langhorne, 1980), the orientation of the electric field determines the strength of the return echo. Therefore this factor must be considered in using the strength of the echo to determine ice properties. Initial analytical work (Rossiter et al., 1980) indicates that it may be possible to estimate the orientation by using two orthogonal antennas. It would be necessary to measure the return echo from each antenna as well as the cross-coupled complnont. Further work on this approach is underway.

In addition to the approaches presented above, standard signal enhancement techniques can be used on impulse radar data, such as averaging consecutive echoes to reduce random noise and pulse compression to delineate echoes more clearly. Although all the above procedures are still in the developing stages at C-CORE, they appear to offer ways of extracting more information from the return signal. Some techniques will prove too slow or cumbersome to use routinely, but we expect others to become an integral part of future ice sounding equipment and operations.

## CONCLUSIONS

It is apparent that under some conditions sea ice can be sounded from airborne platforms. It is also true that not all types of sea ice, in all areas, or at all times, can be sounded by radio techniques. The limitations must be understood by potential users. Airborne use of radar sounders is still in the research stage, but with new types of instrumentation currently being designed, routine operational use is not too far in the future. It is likely that large strides towards an operational system will come not only with new hardware development, but also with greater understanding of the properties of sea ice and with improvements in interpretation techniques. All of these steps need to be followed in future research.

## ACKNOWLEDGEMENTS

Financial support for this work was received from Department of Supply and Services Contract 1SU78-00347; Canadian Marine Drilling, Ltd.; Esso Resources Canada, Ltd.; and the National Research Council of Canada. Generous logistic support from Polar Continental Shelf Project is gratefully acknowledged. It is a pleasure also to acknowledge the many fruitful discussions on this topic with P. Langhorne, L. Davis, B. Mercer, R. Morey, A. Kovacs, R. Lowry, and our colleagues at C-CORE.

## REFERENCES


Butt, K.A., Gamberg, J.B. and Rossiter, J.R. (1979), Remote Estimation of the Properties of Sea Ice, Impulse Radar Study of Lake Melville, Labrador, C-CORE Publication No. 79-7, 248 pp.

Butt, K.A. and Gamberg, J.B. (1980), Technology of an Airborne Impulse Radar, Proc. International Workshop on Remote Estimation of Sea Ice Thickness, St. John's, Sept. 25-26, 1979, In Press.

Campbell, W.J., Ramseier, R.O., Weeks, W.F. and Gloersen, P. (1975), An Integrated Approach to the Remote Sensing of Floating Ice, Proc. Third Canadian Symp. on Remote Sensing, Edmonton, Sept. 22-24, 1975, pp. 39-72.

Davis, J.L. (1980), Electrical Property Measurements of Sea ice In Situ Using a Wideband Borehole Radar and a Time-Domain Reflectometer, Proc. International Workshop on Remote Estimation of Sea Ice Thickness, St. John's, Sept. 25-26, 1979, In Press.

Kovacs, A. and Morey, R.M. (1979), Anisotropic Properties of Sea Ice in the 50- to 150-MHz Range, J. Geophys. Res., vol. 84, pp. 5749-5759.

Langhorne, P.J. (1980), Crystal Anisotropy in Sea Ice, Proc. International Workshop on Remote Estimation of Sea Ice Thickness, St. John's, Sept. 25-26, 1979, In Press.

Langhorne, P.J., Rossiter, J.R. and Keliher, T.E. (1980), Remote Estimation of the Properties of Sea Ice, Ice Core Analysis, Beaufort Sea, March 1979, C-CORE Data Report, In Preparation.

Mercer, J.B. (1980), Remote Sounding of Sea Ice - Past, Present, and Future Applications, Proc. International Workshop on Remote Estimation of Sea Ice Thickness, St. John's, Sept. 25-26, 1979, In Press.

Rossiter, J.R., Langhorne, P., Ridings, T. and Allan, A.J. (1977), Study of Sea Ice Using Impulse Radar, Proc. Fourth Intl. Conf. on Port and Ocean Eng. under Arctic Conditions, St. John's, Sept. 26-30, 1977, pp. 556-567.

Rossiter, J.R. and Butt, K.A. (1979), Remote Estimation of the Properties of Sea Ice, Beaufort Sea Field Trip Report - March 1979, C-CORE Publication No. 79-9, 36 pp.

Rossiter, J.R. (1980), Review of Impulse Radar Sounding of Sea Ice, Proc. International Workshop on Remote Estimation of Sea Ice Thickness, St. John's, Sept. 25-26, 1979, In Press.

Rossiter, J.R., Gamberg, J.B., Gidney, G., Santos, R. and Snellen, J.B. (1980), Remote Estimation of the Properties of Sea Ice, Analytical Techniques for Radar Sounding Data, C-CORE Technical Report, In Preparation.

Rossiter, J.R. and Bazeley, D.P. (1980), ed. Proc. International Workshop on Sea Ice Thickness, St. John's, Sept. 25-26, 1979, C-CORE Publication No. 80-5, In Press.

Snellen, J.B. and Rossiter, J.R. (1980), Remote Estimation of the Properties of Sea Ice, Surface Measurements, Beaufort Sea, March 1979, C-CORE Data Report, In Preparation.

Figure 1 Location of field sites for impulse radar experiment, Beaufort Sea, March 1979.

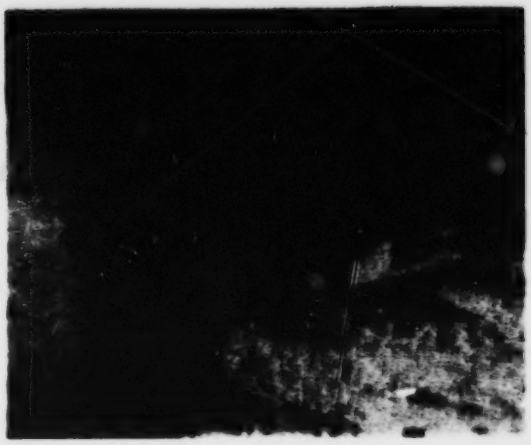

Figure 3 Impulse radar antenna, 200 MHz centre-frequency, mounted under a de Havilland Twin Otter directly aft of the nose wheel. This installation was the first reported use of impulse radar from a fixed-wing aircraft.

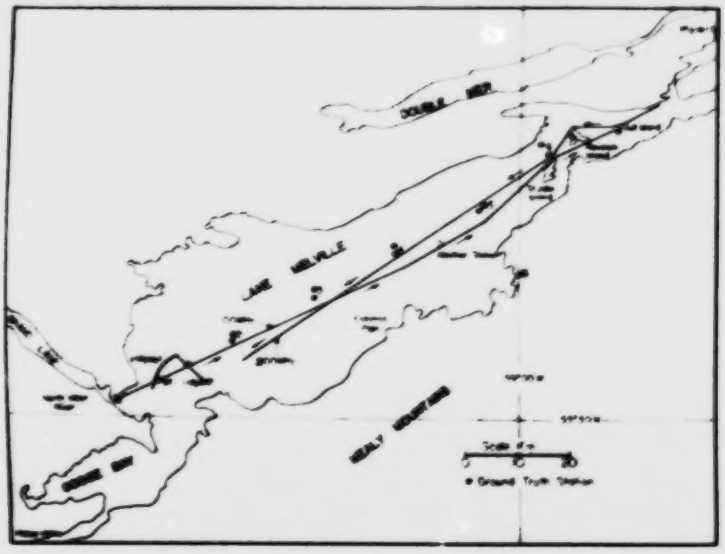

Figure 2 Location of field sites for impulse radar flight paths and ground truth locations, Lake Melville, April 1979.

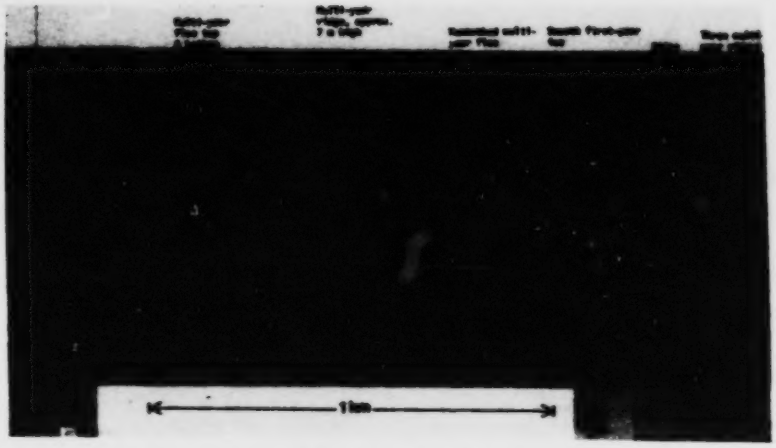

Figure 4 Airborne impulse radar profile taken from a Twin Otter at 30 m elevation and 50 m/s airspeed using a centre frequency of approximately 200 MHz. Multi-year floes typically have moderately rough hummocked upper surface; however, penetration appears to be variable from floe to floe. Reflections from the top of smooth first-year ice are strong; reflections from first-year ridges are very weak due to random scattering. The multi-year floe at the left with a clear bottom echo has an interpreted thickness of 2-3 m, assuming a dielectric constant of 3.5 for the ice. Symbols represent positions on aerial photograph in Figure 5 (Courtesy Canadian Marine Drilling, Ltd.).

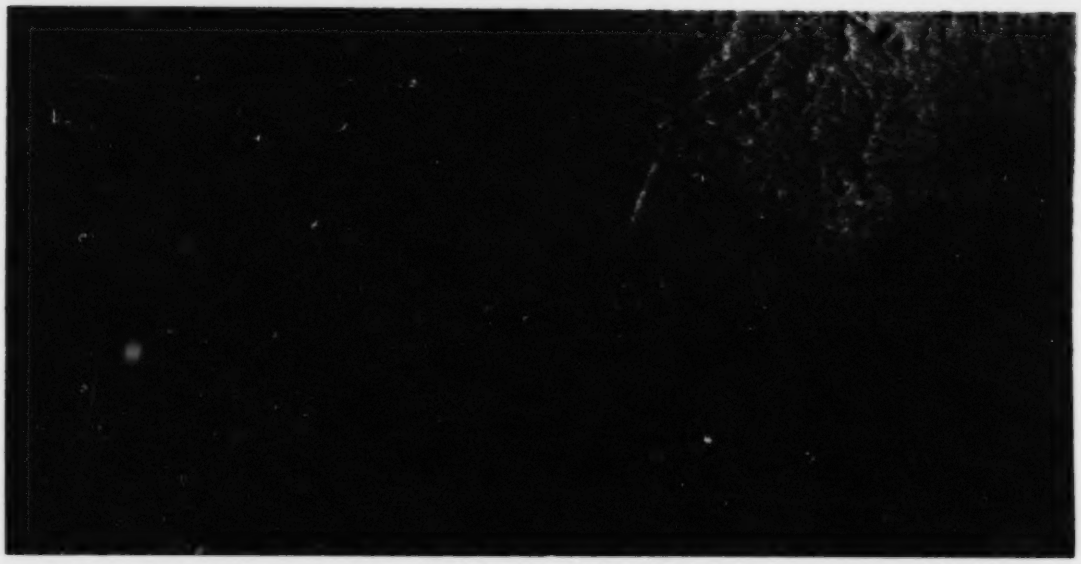

Figure 5 Aerial photograph taken simultaneously with the radar record in Figure 4, but at an altitude of 2440 m. Solid line shows the flight path of the radar aircraft, which can be seen circled in the photograph. Various ice features, indicated by the different symbols, can be correlated with the radar record in Figure 4 (Courtesy Esso Resources Canada, Ltd.).

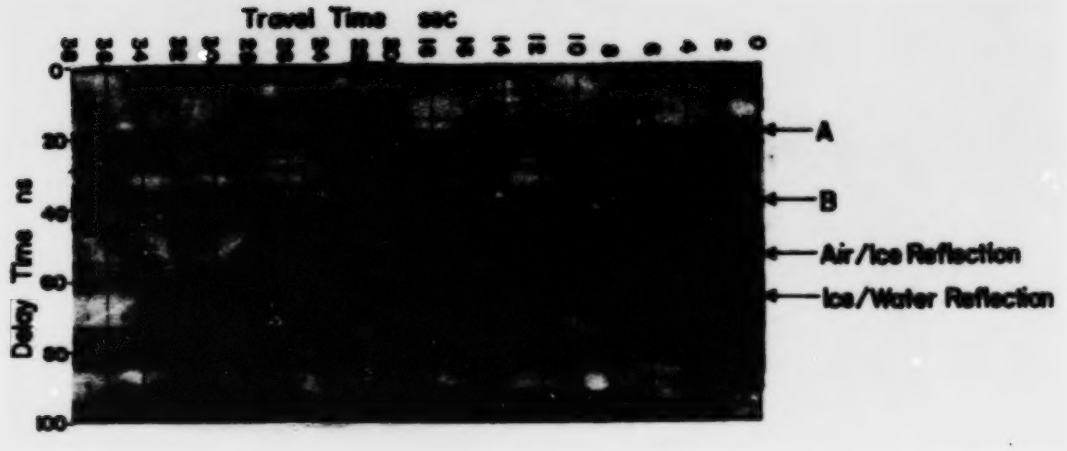


Figure 6 Airborne impulse radar profile over site C-4, taken from a helicopter flying at approximately 10 m elevation and using a centre frequency of approximately 80 MHz. The horizontal bands marked "A" and "B" are systematic interference from the helicopter. This first-year sea ice had a thickness of approximately 1.15 m. Helicopter altitude increased to the left, beyond 28 sec. travel time. Vertical dashed lines are event markers; hyperbolic echoes are from reflectors placed on the ice surface.

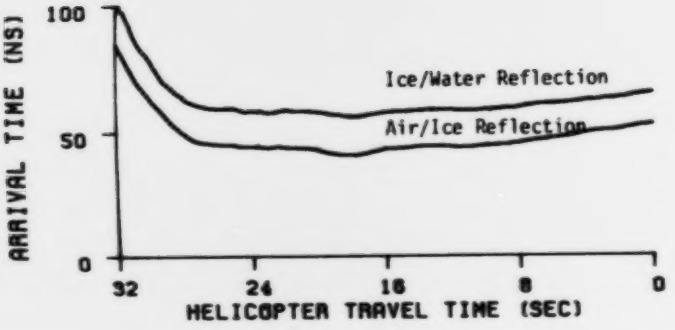


Figure 7 Pulse arrival times from Figure 6 calculated using cross-correlation technique. Agreement with measured ice thickness was obtained using a dielectric constant of 3.7.

POOR

QUALITY

ORIGINAL